REPORT DOCUMENTATION PAGE	Form Approved OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE 12/15/01	3. REPORT TYPE AND DATES COVERED Final 31 March 2000 – ~~December 2001~~ 15 Sep 01
4. TITLE AND SUBTITLE **Growth and Characterization of High Frequency Materials** DAAD19-00-1-0054		5. FUNDING NUMBERS G DAAD19-00-1-0054
6. AUTHOR(S) Dr. R.E. Camley Dr. Z. Celinski		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Drs. R.E. Camley and Z. Celinski Department of Physics, University of Colorado at Colorado Springs 1420 Austin Bluffs Parkway, Colorado Springs, CO 80918		8. PERFORMING ORGANIZATION REPORT NUMBER REC121501
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) U. S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211		10. SPONSORING / MONITORING AGENCY REPORT NUMBER 40779.1-PH-RIP
11. SUPPLEMENTARY NOTES The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.		
12 a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution unlimited.		12 b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

This instrumentation award had following objectives:

1. Obtain a sputtering deposition system
2. Upgrade a UHV system to a Molecular Beam Epitaxy system
3. Build new FMR (ferromagnetic resonance) systems
4. Upgrade BLS (Brillouin Light Scattering) system

All of these objectives have been accomplished. We purchase a sputtering system equipped with 5 guns and e-beam system. We upgraded deposition system to a single chamber MBE system. We built four FMR systems working at 24, 35, 45 and 55 GHz and upgraded our BLS system. The details are provided in the narrative part of this report.

14. SUBJECT TERMS Instrumentation Award	20020201 114	15. NUMBER OF PAGES 6
		16. PRICE CODE

17. SECURITY CLASSIFICATION OR REPORT	18. SECURITY CLASSIFICATION ON THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev.2-89)
Prescribed by ANSI Std. 239-18
298-102

University of Colorado at Colorado Springs

College of Letters, Arts and Sciences

1420 Austin Bluffs Parkway
P.O. Box 7150
Colorado Springs, Colorado 80933-7150

December 15, 2001

Dr. Mikael Ciftan
US Army Research Office
P. O. Box 12211
Research Triangle Park, NC 27709

Dear Mikael,

Please find enclosed the final report for our instrumentation grant. This instrumentation grant REALLY helped us. We obtained a sputtering system and created 4 new ferromagnetic resonance systems (24 GHz, 35 GHz, 45 GHz and 55 GHz) and upgraded our Brillouin Light Scattering (BLS) system and finally built a second Molecular Beam Epitaxy (MBE) system. All this equipment is now actively in use and is helping substantially in our effort to study the physics of magnetic materials at high frequencies and to develop high frequency applications. Thank you so very much for your support.

Sincerely

Zbigniew Celinski Bob Camley

Z. Celinski and R. E. Camley

MASTER COPY: PLEASE KEEP THIS "MEMORANDUM OF TRANSMITTAL" BLANK FOR REPRODUCTION PURPOSES. WHEN REPORTS ARE GENERATED UNDER THE ARO SPONSORSHIP, FORWARD A COMPLETED COPY OF THIS FORM WITH EACH REPORT SHIPMENT TO THE ARO. THIS WILL ASSURE PROPER IDENTIFICATION. NOT TO BE USED FOR INTERIM PROGRESS REPORTS; SEE PAGE 2 FOR INTERIM PROGRESS REPORT INSTRUCTIONS.

MEMORANDUM OF TRANSMITTAL

U.S. Army Research Office
ATTN: AMSRL-RO-BI (TR)
P.O. Box 12211
Research Triangle Park, NC 27709-2211

- ☐ Reprint (Orig + 2 copies)
- ☐ Manuscript (1 copy)
- ☐ Technical Report (Orig + 2 copies)
- ☒ Final Progress Report (Orig + 2 copies)
- ☐ Related Materials, Abstracts, Theses (1 copy)

CONTRACT/GRANT NUMBER: DAAD19-00-1-0054

REPORT TITLE: Growth and Characterization of High Frequency Materials

is forwarded for your information.

SUBMITTED FOR PUBLICATION TO (applicable only if report is manuscript):

Sincerely,

Zbigniew Celinski

Enclosure 3

Growth and Characterization of High Frequency Materials

(DAAD19-00-1-0054)

Statement of Major Problems Studied

The frequency range of 10-100 GHz has become increasingly important for commercial and military communication and tracking. We are working on developing new magnetic materials and devices that can be useful for signal processing in this range. To do this we requested funds to improve our capabilities for the growth of high-quality magnetic materials and for the characterization of these materials. In specific we requested funds for the following:

1. Obtain a sputtering deposition system
2. Upgrade a UHV system to a Molecular Beam Epitaxy system
3. Build new FMR (ferromagnetic resonance) systems
4. Upgrade BLS (Brillouin Light Scattering) system

All of these tasks have now been accomplished. The sputtering system has been delivered and has created its first samples. In the upgrade of the UHV system to an MBE we installed UHV linear e-gun, RHEED system, thickness monitor and cryo-pumps. In addition we modified an existing UHV manipulator to work in this system. We created 4 new ferromagnetic resonance systems (24 GHz, 35 GHz, 45 GHz and 55 GHz). A low temperature dewar for measurements from room temperature to 24 K was purchased and implemented on the 24 GHz system. The BLS system was upgraded by adding new software and new electronics for the the Fabry-Perot interferometer. A second electro-magnet which allows us to reach 8.5 kG was also installed.

A further portion of the instrumentation grant proposal read "This equipment will be used to train students of all levels (undergraduates through PhD) in the growth and characterization of magnetic based devices." This too has been accomplished. We list below the students working on this equipment.

High School Students:		
Brian Camley	Ben Haeffele	Michael Subialka
Christopher Bohm	Reginald Kerr	
Undergraduates:		
Tammy O'Keevan	Andrew Hutchison	Carl Coffield
Graduates students:		
Nick Cramer		
Post-Doctoral		
Leszek Malkinski	Bijoy Kuanr	

Publications:

Although this was an instrumentation grant, it did result in one publication. We certainly expect additional publications based on work with the equipment purchased under this grant.

M. Hekert, D. Tietjen, C. Schneider, N. Cramer, L. Malkinski, R.E. Camley, and Z. Celinski, "Thermal stability and degradation mechanism of NiFe/Cu GMR multilayer systems" J. Appl. Phys. (in press)

FINANCIAL STATUS REPORT

(Short Form)

(Follow instructions on the back)

1. Federal Agency and Organizational Element to Which Report is Submitted	2. Federal Grant or other Identifying Number Assigned By Federal Agency	OMB Approval No.	Page	of
Army Research Office	**DAAD19-00-1-0054**		1	1 pages

3. Recipient Organization (Name and complete address, including ZIP code)
UNIVERSITY OF COLORADO AT COLORADO SPRINGS
ACCOUNTING OFFICE-CONTRACTS AND GRANTS
PO BOX 7150
COLORADO SPRINGS, CO 80933-7150

4. Employer Identification Number	5. Recipient Account Number or Identifying Number	6. Final Report	7. Basis
184-60000555	**4537308**	☐ Yes ☐ No	☒ Cash ☐ Accrual

8. Funding/Grant Period *(See Instructions)* From: (Month, Day, Year)	To: (Month, Day, Year)	9. Period Covered by this Report From: (Month, Day, Year)	To: (Month, Day, Year)
4/1/00	**9/15/01**	**3/31/00**	**9/15/01**

10. Transactions:	I Previously Reported	II This Period	III Cumulative
a. Total Outlays	**0.00**	**145,000.00**	**145,000.00**
b. Recipient share of outlays	**0.00**	**10,000.00**	**10,000.00**
c. Federal share of outlays	**0.00**	**135,000.00**	**135,000.00**
d. Total unliquidated obligations	**0.00**	**0.00**	**0.00**
e. Recipient share of unliquidated obligations	**0.00**	**0.00**	**0.00**
f. Federal share of unliquidated obligations	**0.00**	**0.00**	**0.00**
g. Total Federal share *(Sum of lines c and f)*	**0.00**	**135,000.00**	**135,000.00**
h. Total Federal funds authorized for this funding period		**135,000.00**	**135,000.00**
i. Unobligated balance of Federal funds*(Line h minus line g)*	**0.00**	**0.00**	**0.00**

11. Indirect Expense

a. Type of Rate *(Place "X" in appropriate box)*
☐ **Provisional** ☒ **Predetermined** ☐ **Final** ☐ **Fixed**

b. Rate	c. Base	d. Total Amount	e. Federal Share
48%	**-**	**-**	**0.00**

12. *Remarks: Attach any explanations deemed necessary or information required by Federal sponsoring agency in compliance with governing legislation.*

13. Certification: **I certify to the best of my knowledge and belief that this report is correct and complete and that all outlays and unliquidated obligations are for the purposes set forth in the award documents.**

Typed or Printed Name and Title	Telephone (Area code, number, and extension
Milagros Togade, Accountant	719-262-3482
Signature of Authorized Certifying Official	**Date Report Submitted**
Milagros Togade	12/14/01

REQUEST FOR ADVANCE OR REIMBURSEMENT

Standard Form 270

OMB APPROVAL NO.			PAGE 1 of 1
1 TYPE OF PAYMENT REQUESTED	a. *"X" one, or both boxes* ADVANCE REIMBURSEMENT X b. *"X" the applicable box* FINAL X PARTIAL		2. BASIS OF REQUEST CASH X ACCRUAL

3. FEDERAL SPONSORING AGENCY AND ORGANIZATIONAL ELEMENT TO WHICH THIS REPORT IS SUBMITTED Army Research Office	4. FEDERAL GRANT OR OTHER IDENTIFYING NUMBER ASSIGNED BY FEDERAL AGENCY DAAD19-00-0054	5. PARTIAL PAYMENT REQUEST NUMBER FOR THIS REQUEST

6. EMPLOYER IDENTIFICATION NUMBER 84-6000555	7. RECIPIENT'S ACCOUNT NUMBER OR IDENTIFYING NUMBER 4537308	**8. PERIOD COVERED BY THIS REQUEST** FROM 03/31/00	TO 9/15/00

9. RECIPIENT ORGANIZATION Name:University of Colorado, Colorado Springs Sponsored Programs Accounting P.O. BOX 7150 COLORADO SPRINGS, CO 80933-7150	10. PAYEE *(Where check is to be sent is different than item 9)* *Name:* SAME as Box 9 *Number and Street:* *City, State and ZIP Code:*

11. COMPUTATION OF AMOUNT OF REIMBURSEMENTS/ADVANCES REQUESTED

PROGRAM/ FUNCTIONS/ ACTIVITIES		*(a)*	*(b)*	*(c)*	TOTAL
a. Total program outlays to date *(As of date)*		$	$	$	**145,000.00**
b. *Less:* Cumulative program income					
c. Net program outlays *(Line a minus line b)*					145,000.00
d. Estimated net cash outlays for advance period					
e. Total *(Sum of lines c & d)*					145,000.00
f. Non-Federal share of amount on line e					10000
g. Federal share of amount on line e					135,000.00
h. Federal payments previously requested					131,625.00
i. Federal share now requested *(Line g minus line h)*					3,375.00
j. Advances required by month, when requested by by Federal grantor agency for use in making prescheduled advances	**1st month**				
	2nd month				
	3rd month				

12. ALTERNATE COMPUTATION FOR ADVANCES ONLY

a. Estimated Federal cash outlays that will be made during period covered by the advance	$
b. *Less:* Estimated balance of Federal cash on hand as of beginning of advance period	
c. Amount requested *(Line a minus line b)*	$

13. CERTIFICATION

I certify that to the best of my knowledge and belief the data above are correct and that all outlays were made in accordance with the grant conditions or other agreement and that payment is due and has not been previously requested.	NAME AND TITLE [signature] 10/14/01 ACCOUNTANT III	TELEPHONE (AREA CODE, NUMBER, EXTENSION) 719-262-3482

This information will be submitted to the Grants Management Division

RESEARCH AGREEMENT NO. DAA19-00-1-0054

810100 50% DOWN PAYMENT FOR 1 EACH	5/3/2000	44,950.00
530101 T F S TECHNOLOGIES CELINSKI	5/12/2000	1,958.52
810100 50% BALANCE PAYMENT FOR 1 EACH	11/8/2001	44,950.00
SPUTTERING DEPOSITION SYSTEM		**$ 91,858.52**
530101 CAMERAWORKS CELINSKI	4/21/2000	245.00
810100 CRYOSTAT SYSTEM, SPECIAL MODEL	11/9/2000	16,131.80
530101 JRS SCIENTIFIC INSTRUMENTS	12/19/2000	1,416.45
FMR (FERROMAGNETIC RESONANCE) SYSTEMS BLS (BRILLOUIN LIGHT SCATTERING) SYSTEM		**$ 17,793.25**
530101 LAB EQUIPMENT	4/7/2000	1,778.38
530101 HSD ENGINEERING INC CELINSKI	4/12/2000	339.90
530101 DUNIWAY STOCKROOM C CELINSKI	4/21/2000	140.43
537600 ADAMANT COMPUTERS CELINSKI	4/21/2000	570.31
530101 K SPACE ASSOCIATES CELINSKI	4/25/2000	2,214.05
530101 RBD ENTERPRISES CELINSKI	5/5/2000	2,564.68
530101 RBD ENTERPRISES CELINSKI	5/5/2000	912.71
537600 ADAMANT COMPUTERS CELINSKI	5/9/2000	896.40
530101 K SPACE ASSOCIATES CELINSKI	5/16/2000	500.00
530101 APPLIED VACUUM TECH CELINSKI	8/4/2000	919.83
530101 KURT J LESKER CO CELINSKI	8/14/2000	80.00
530101 ACOUSTICAL SOLUTION REHORST	8/23/2000	278.44
530101 RBD ENTERPRISES CELINSKI	8/23/2000	2,340.00
530101 LAB EQUIPMENT	9/9/2000	2,300.00
530101 LAB EQUIPMENT	11/20/2000	3,788.45
530101 STRUCTURE PROBE CELINSKI	11/27/2000	109.16
530101 THERMIONICS NORTHWE CELINSKI	12/5/2000	1,215.58
530101 LAB EQUIPMENT	1/31/2001	2,870.00
530101 REPAIR CRYOPUMP MODEL APD-8	4/14/2001	3,504.00
530101 LAB & TECH SHOP SUPPLIES	11/27/2001	(1,974.09)
UHV SYSTEM UPGRADE TO MOLECULAR BEAM EPITAXY SYSTEM		**$ 25,348.23**
TOTAL		**$ 135,000.00**

BUDGET:

SPUTTERING DEPOSITION SYSTEM	95,000.00
UHV SYSTEM UPGRADE TO MOLECULAR BEAM EPITAXY SYSTEM	35,000.00
FMR (FERROMAGNETIC RESONANCE) SYSTEMS	10,000.00
BLS (BRILLOUIN LIGHT SCATTERING) SYSTEM	5,000.00
	145,000.00
PAID BY UNIVERSITY OF COLORADO AT COLORADO SPRINGS	(10,000.00)
	135,000.00

Thermal stability and degradation mechanism of NiFe/Cu GMR multilayer systems

M. Hecker, D. Tietjen, C.M. Schneider,

IFW Dresden, P.O.B. 270016, 01171 Dresden, Germany

N. Cramer, L. Malkinski, R.E. Camley, and Z. Celinski

Department of Physics, UCCS, Colorado Springs, USA

Abstract

$Ni_{80}Fe_{20}/Cu$ multilayers show large giant magneto resistance (GMR) at low magnetic saturation fields. The GMR signal is known to degrade irreversibly at elevated temperatures. Clarification of the relevant deterioration mechanisms refines our basic understanding of the GMR effect and may help to improve the thermal stability of devices. We therefore investigated structural, transport and magnetic properties of sputtered $Ni_{80}Fe_{20}/Cu$ multilayers in the as-deposited state and after different anneals (up to 600°C) by X-ray techniques, transport measurements, ferromagnetic resonance (FMR) and magneto-optical Kerr effect (MOKE). Multilayers with the second maximum of the antiferromagnetic (afm) coupling showed a sharp drop of the GMR at about 250°C. The changes of the transport properties were associated with a series of structural alterations. These ranged from grain growth and defect reduction through texture sharpening and stress evolution up to the onset of interdiffusion. Interdiffusion changed the NiFe layer composition and the interface structure and finally caused layer intermixing with a loss of the former multilayer structure. Further insight into the magnetic behavior was gained from FMR and MOKE measurements, from which we determined the in-plane magnetic anisotropies, the strength of the afm coupling (bilinear and biquadratic) and the homogeneity of the layer magnetization as a function of the annealing temperature.

The discoveries of antiferromagnetic exchange coupling[1] and giant magnetoresistance (GMR) effects[2,3,4] have opened a possibility for novel applications in different areas, such as magnetic recording, non-volatile memories and magnetic sensors. One of the most important applications was the development of spin valve structures by IBM[5]. In order to optimise the performance of magnetic devices, many different material combinations have been studied to obtain optimum properties. Among them, the Ni_xFe_{1-x}/Cu ($x \approx 0.81$, in the following denoted as NiFe or Permalloy) system[6,7] has attracted significant attention due to the low anisotropy in permalloy, the small saturation magnetic field and negligible hysteresis effects.

The performance of the magnetic devices based on the NiFe/Cu material combination must withstand different working conditions, such as elevated temperature and mechanical stress. Depending on the individual layer thickness, an irreversible degradation of the GMR occurs in NiFe/Cu multilayers at elevated temperatures[8]. However, little is known about the underlying individual deterioration mechanisms; one must perform comprehensive structural analysis in order to understand these mechanisms. For multilayers with 100 nm individual layer thicknesses and thicker, structural investigations by Auger electron spectroscopy (AES) and XRD indicated the onset of Ni diffusion into the Cu layers above a critical temperature[9]. The present investigation concerned the question of how the degradation of the magnetic properties is correlated with irreversible structural changes for *nanoscaled* GMR multilayers. To do this, we used a whole spectrum of methods, including X-ray diffraction and reflectometry, electron microscopy, measurements of the transport properties, magneto-optical Kerr effect (MOKE) and ferromagnetic resonance (FMR).

We employed DC magnetron sputtering to deposit $[\mathrm{NiFe(1.7nm)+Cu(2.1nm)}]_{30}$ + NiFe(1.7nm) structures onto thermally oxidized Si (001) wafers in an Ar atmosphere of 60 mbar. The Cu layer thickness corresponded to the second afm maximum in the NiFe/Cu system. We

employed a Philips-XPert diffractometer with Cu-K_α radiation to carry out the X-ray diffraction experiments and a standard 4-point probe set-up to measure the transport properties. We conducted anneals for one hour in vacuum (pressure 10^{-6} mbar) at different temperatures (T_{an}) in the range between 75 °C and 600 °C. After the anneals, we carried out structural, transport and magnetic measurements at room temperature.

The GMR effect in the as-deposited structures was on the level of 10%. Annealing up to 220 °C increased the GMR to 12%, however, additional annealing (at 300 °C or higher temperatures) resulted in a sharp decrease of the GMR signal (see Figure 1). We found that the total resistivity of the samples was nearly constant up to 220 °C and strongly increased after annealing at 300 °C. The saturation field behaved in a similar fashion, it was nearly constant (approximately 80 Oe) for annealing up to 220 °C and then increased dramatically to approximately 1500 Oe for higher annealing temperatures.

To correlate the changes in the GMR properties with possible changes of the interface properties, we used X-ray reflectometry (XRR). The XRR patterns clearly showed that the bilayer sequence is stable up to an annealing temperature of 300 °C[10]. For higher annealing temperatures we observed degradation of the layered structure, which completely intermixed after annealing at 600 °C. In contrast, the total thickness of the metallic structure (120 nm) was preserved even after annealing at 600 °C. From simulation calculations of the XRR curves, we calculated the mean roughness parameter (σ) of the interfaces to be 0.5 nm up to T_{an} ~ 250 °C, followed by a sharp increase to values above 1 nm at T_{an} ~ 400 °C.

The wide angle diffraction patterns (Fig. 2) indicated that a predominantly <111> texture was preserved during annealing. Even the texture sharpened during annealing, i.e., the half-width of the pole figure cuts decreased[10]. The grains possessed a typical vertical size of approximately 25 nm after deposition and showed a columnar structure. Annealing at T_{an} > 220 °C increased the

grain size significantly, causing a growth of a certain fraction of grains through the complete layer stack, as seen also in Co/Cu multilayers[11]. Still more striking was the lateral grain growth, which lead to maximum grain sizes in the micrometer range and a mean size of 700 nm after the 400 °C anneal. This was measured using the electron back scattering diffraction (EBSD) technique in a SEM. AES measurements of NiFe(100 nm)/Cu(200 nm) stacks showed the onset of interdiffusion at 250 °C, when Ni atoms preferentially diffused into the Cu layers[9]. The X-ray and AES measurements indicated that anneals above 250 °C strongly affected the multilayer structure. The strong increase in grain size and roughness parameters, in combination with preferential interdiffusion of Ni into Cu, finally resulted in a complete destruction of the layered NiFe/Cu structure. More detailed results of the XRR and of the texture studies are presented elsewhere[10].

We performed magnetic measurements at room temperature as a function of the angle within the film plane. Figure 3 shows hysteresis loops measured by MOKE for different orientations. The change in the shape of the hysteresis loops for different angles (only two shown) clearly indicated the presence of a uniaxial in-plane anisotropy. Measurements along one direction yielded "S"-shaped loops (hard axis) and for measurements 90° off this axis we observed hysteresis loops that are typical for afm coupled systems. The value of the saturation along the easy axis (approximately 75 Oe) was in agreement with the GMR measurement for the as-deposited samples. The shape of the hysteresis loop along the easy axis was typical for the presence of both biquadratic and bilinear coupling contributions. Two critical fields were seen. The first represented the initial deviation from the collinear (saturated) configuration and the second represented a field at which the neighbouring layers became antiparallel. From these measurements, we determined the strength of both, the bilinear (J_1) and the biquadratic (J_2) exchange coupling[12] ($J_1 = -0.0012$ erg/cm^2 and $J_2 = 0.001$ erg/cm^2) and the strength of the small

uniaxial in-plane anisotropy (H_u = 20 Oe). The strength of the exchange coupling was very small and nearly constant up to $T_{an} \sim 260$ °C. At this temperature the hysteresis loops showed visible deformations with respect to the as-grown data. Instead of two well-defined critical fields we observed a few smaller jumps that indicated different switching fields in different regions of the sample.

The FMR measurements confirmed the presence of the uniaxial in-plane anisotropy and resulted in values that were similar to those determined by the fitting of the MOKE data[13]. The uniaxial in-plane anisotropy (20 ± 5 Oe) was nearly constant up to $T_{an} \sim 260$ °C. Then we observed a significant increase to 60 Oe at $T_{an} \sim 330$ °C. The $4\pi M_{eff}$ behaved in a similar fashion. Up to 260 °C, the value of $4\pi M_{eff}$ was nearly constant at 6.5 kG; this was followed by a rapid decrease to 5.6 kG at 330 °C.

The measurements of the FMR linewidth revealed an interesting behaviour. The line width was nearly constant (ΔH = 120 Oe) up to $T_{an} \sim 150$ °C. After annealing at 180 °C the linewidth decreased to 75 Oe. However, after annealing at higher temperatures we observed increased values of the linewidth, which reached a maximum value of 250 Oe after annealing at 330 °C – see Figure 4. The observed minimum of the linewidth corresponded well to the increased GMR at this annealing temperature--a finding that was discussed in more detail by Hecker, et. al.[10].

All our experimental results pointed to a temperature of approximately 250 °C, at which we found critical changes in our NiFe/Cu structures. We observed two tendencies. First, for annealing below 250 °C, there was an increase of the grain size and a reduction of defects, as inferred from the XRD experiments. This tendency corresponded to the observed decrease in FMR linewidth, which indicated increased magnetic homogeneity of our layers near an annealing temperature of 200 °C. Second, for annealing temperatures above 250 °C, we observed a

significant intermixing between Ni and Cu that degraded the structural and magnetic integrity of the NiFe/Cu layers. The multilayer structure became less defined, and as a result we observed a significant degradation of the GMR effect. In conclusion, it is the alloying tendency of Ni and Cu above 250 °C that determined the decay of the GMR and the change in the magnetic properties of our NiFe/Cu multilayers.

Acknowledgement

We acknowledge financial support from DAAD (315/PPP), the National Science Foundation (INT-9815225 and DMR-9970789), US Army Research Office (DAAG55-98-0294 and DAAD19-00-1-0054) and the SFB422.

Figure Captions:

Fig. 1 Maximum resistance at zero magnetic field (R_{max}), saturation resistance (R_{sat}) and GMR versus annealing temperature

Fig. 2 Wide angle X-ray diffraction patterns showing the zeroth order {111} and {200} reflection of the NiFe/Cu multilayers

Fig. 3 The hysteresis loops measured along different axes (easy and hard)

Fig. 4 FMR linewidth as a function of annealing temperature, measured at 24 GHz

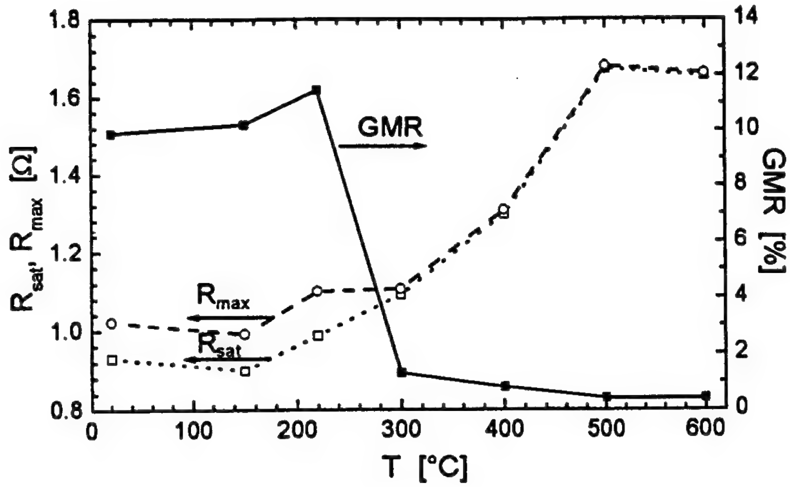

Figure 1 (M. Hecker et al., Journal of Applied Physics)

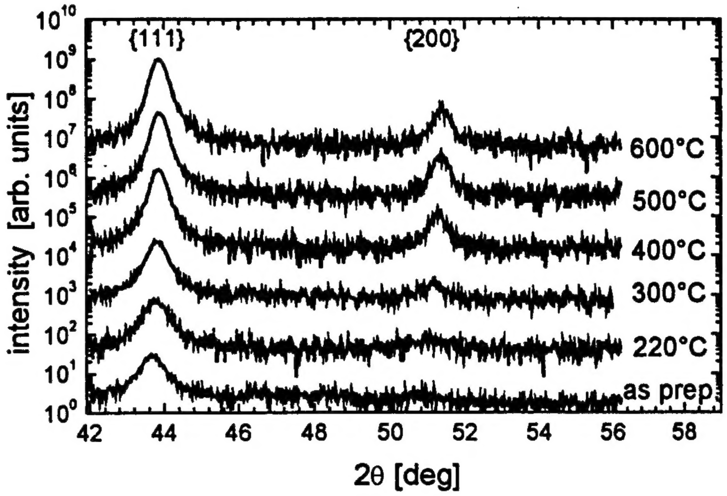

Figure 2 (M. Hecker et al., Journal of Applied Physics)

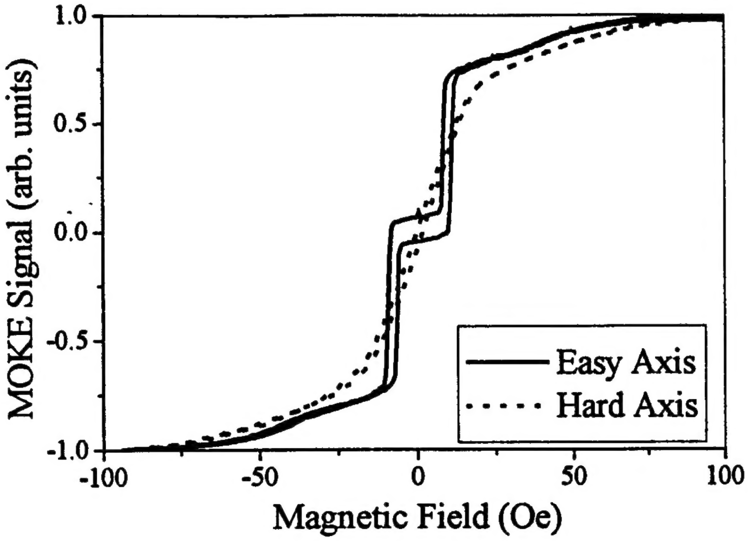

Figure 3 (M. Hecker et al., Journal of Applied Physics)

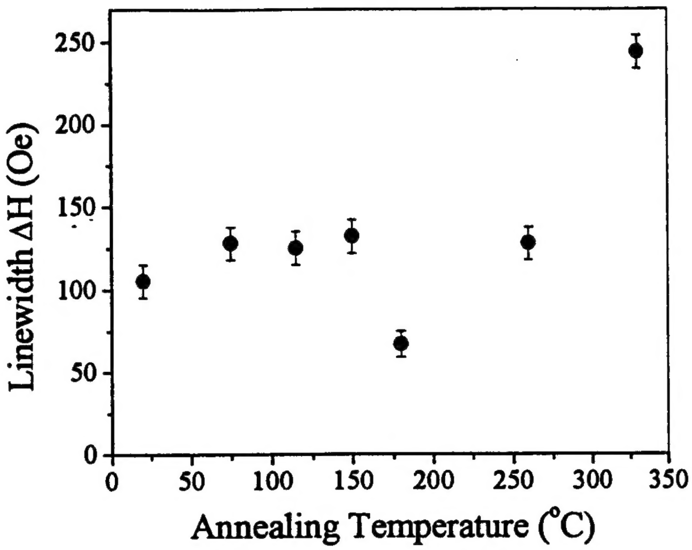

Figure 4 (M. Hecker et al., Journal of Applied Physics)

References:

[1] J. Grünberg, R. Schreiber, Y. Pang, M.B. Brodsky, H. Sowers, Phys. Rev. Lett., **57**, 2442 (1986)

[2] M.N. Baibich, J.M. Broto, A. Fert, F. Nguyen Van Dau, F. Petroff, P. Etienne, G. Creuzet, A. Frederich, J. Chazelas, Phys. Rev. Lett., **61**, 2472 (1998).

[3] G. Binash, P. Grünberg, F. Saurenbach, W. Zinn, Phys. Rev. B, **39**, 4828 (1989)

[4] A. Fert and P. Bruno, Interlayer Coupling and Magnetoresistance in Multilayers in B. Heinrich and J.A.C. Bland (Eds.) Ultrathin Magnetic Structures II, Springer, New York 1994, p 82.

[5] B.A. Gurney, D.R. Wilhoit, V.S. Speriosu, and I.L. Sanders, IEEE Tran. Magn., 26, 2747 (1990)

[6] S.S. Parkin, Appl. Phys. Lett., **60**, 512 (1992).

[7] A. Hütten, S. Mrozek, S. Heitmann, T. Hempel, H. Brückl, and G. Reiss, Acta. mater. **47** (1999) 4245.

[8] L.van Loyen, D. Elefant, D. Tietjen, C.M. Schneider, M. Hecker, J. Thomas; J. Appl. Phys. **87**, 4852 (2000).

[9] W. Brückner, S. Baunack, M. Hecker, J.-I. Mönch, L.v. Loyen, C.M. Schneider, Appl. Phys. Lett. 77, 358 (2000).

[10] M. Hecker, D. Tietjen, H. Wendrock, C.M. Schneider, N. Cramer, L. Malkinski, R.E. Camley , and Z. Celinski, submitted to J. Magn. Magn. Mat.

[11] M. Bobeth, M. Hecker, W. Pompe, C.M. Schneider, J. Thomas, A. Ullrich, K. Wetzig, Z. Metallkunde. **92** (2001) 810.

[12] J. Slonczewski, Phys. Rev. Lett., **67**, 3172 (1991)

[13] B. Heinrich, A.s. Arrott, J.F. Cochran, K.B. Urquhart, K. Myrtle, Z. Celinski, and Q.M. Zhong, Mat. Res. Soc. Symp. Proc, **151**, (1989) 177.